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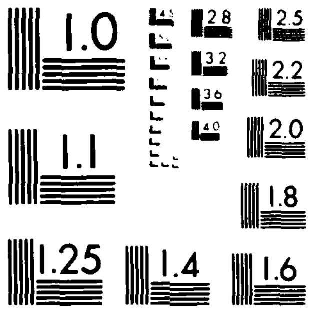

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This study provide relatively simple climatological models for determining the incidence of frost days (minimum daily temperature<0° C), ice days (maximum daily temperature<0°C) and freeze-thaw days (minimum daily temperature<0°C, maximum daily temperature>0° C) throughout Iceland, Greenland, Alaska, and E. Siberia. Both area and station models yield estimates of the frequency of diurnal freeze-thaw cycles per month or year. The various models demonstrate the relationships between daily freezing conditions and the different temperature regimes. The results should improve understanding of periglacial activity and provide a means

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DIURNAL FREEZE-THAW FREQUENCIES IN THE HIGH LATITUDES: A CLIMATOLOGICAL GUIDE

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This study provides relatively simple climatological models for determining the incidence of frost days (minimum daily temperature ≤ 0° C), ice days (maximum daily temperature ≤ 0° C) and freeze-thaw days (minimum daily temperature ≤ 0° C, maximum daily temperature > 0° C) throughout Iceland, Greenland, Alaska, and E. Siberia. Both area and station models yield estimates of the frequency of diurnal freeze-thaw cycles per month or year. The various models demonstrate the relationships between daily freezing conditions and the different temperature regimes. The results should improve understanding of periglacial activity and provide a means of predicting possible climatic effects on the construction of buildings, roads and airport runways.

INTRODUCTION

The impact of diurnal freeze-thaw cycles on soils, rocks, roadbeds, and construction materials is of much concern to the agriculturist, hydrologist, geologist, and transportation or construction engineer. As noted by Troll (1958), such alternation of freezing and thawing not only affects the particular size structure of the soil but also causes erosion, runoff, or flooding and reduces the bearing strength of the surface layer. The vulnerability of the ground depends, among other variables, on the amount of available moisture and whether the ground is bare or is covered with vegetation, ice, or snow.

The surface covering affects the albedo which in turn is largely responsible for local differences in extreme temperatures, that is the daily maximum and minimum, the determining factors of daily freeze-thaw. Daily freezing conditions may be defined as consisting of frost days (min ≤ 0° C), ice days (max ≤ 0° C), and freeze-thaw days (min ≤ 0° C, max > 0° C). The interrelationship among these three variables forms the basis of this study. The principal question is: What incidence of diurnal freeze-thaw cycles may be expected at a given site per given interval of time?

This paper presents information on daily freezing conditions in the permafrost and contiguous regions of Iceland, Greenland, Alaska, and E. Siberia. Also included are several West German stations representing a range of elevations for the comparison of the effects of altitude with those of latitude. As in an earlier study by Wexler (1982), a number of guides are offered for estimating the respective frequencies of frost days, ice days, and freeze-thaw days per month or year for any given site from routine climatological parameters.

BACKGROUND

The geographical distribution of the annual number of diurnal freeze-thaw cycles has been determined for various countries or sections: United States, Canada, Poland, Japan, the Arctic, Europe, and the U.S.S.R (Fraser 1959, Hastings 1961, Hershfield 1972, Pelko 1970, Russell 1943, Shitara 1970, Visher 1945, Wexler 1982, Williams 1964). Annual or monthly frequencies of frost days, ice days, and freeze-thaw days have been correlated respectively with mean daily minimum temperatures, mean daily maximum temperatures, and a combination of both (Fraser 1959, Hershfield 1972, Shitara 1970, Wexler 1982).

DATA

Frequencies of diurnal freeze-thaw cycles are not readily available. Many climatic summaries list frost days, but few list ice days. In the past information on freeze-thaw cycles has sometimes been simulated (Hastings 1961, Visher 1945). In this paper, all the analyses are based on actual observations of frost days and ice days, the data for which were obtained from a variety of sources, mainly: the U.S. Department of Commerce (1980), the Danske Meteorologiske Institute (1947-1965), and U.S. Air Force Environmental Technical Applications Center (1978). All the temperatures referred to in this paper were from standard weather shelters at 1.5 to 1.8 m above ground.

FROST DAYS AND ICE DAYS

For a network of stations in a given region observations were obtained of: The mean daily minimum temperature, N, the mean daily maximum temperature, M, the number of frost days, F, and the number of ice days, I, per month and year. From these observations, simple linear regression models were determined such that F may be derived from N and I may be derived from M for any site within the specified region per given interval of time. Figure 1 gives examples of these regression plots for annual data for Alaska, E. Siberia, Iceland, and Greenland. Figure 2 contains similar plots for monthly data for May, Greenland and April for the other areas. The corresponding regression equations are of the form:

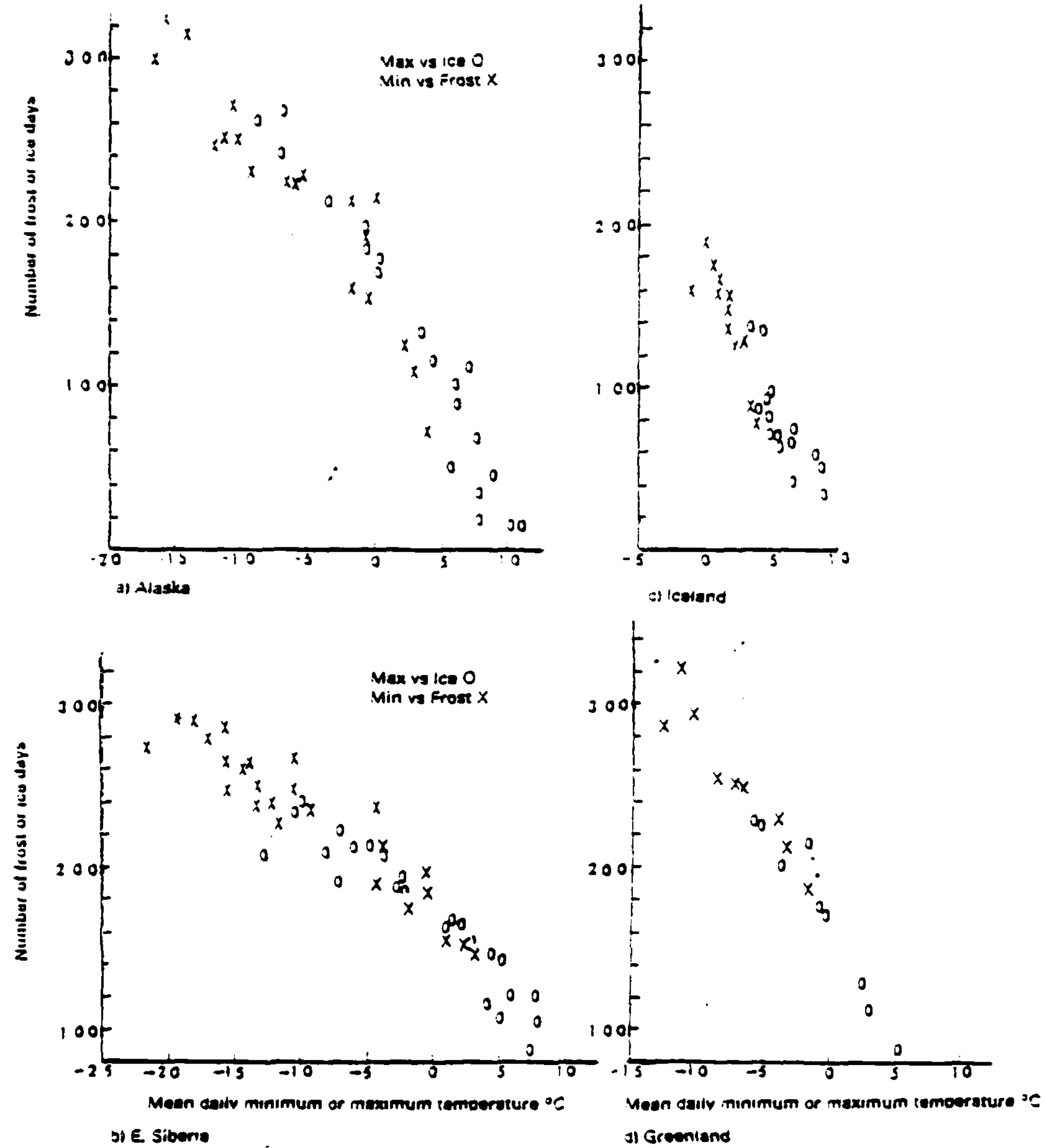

Figure I Annual data for selected regions.

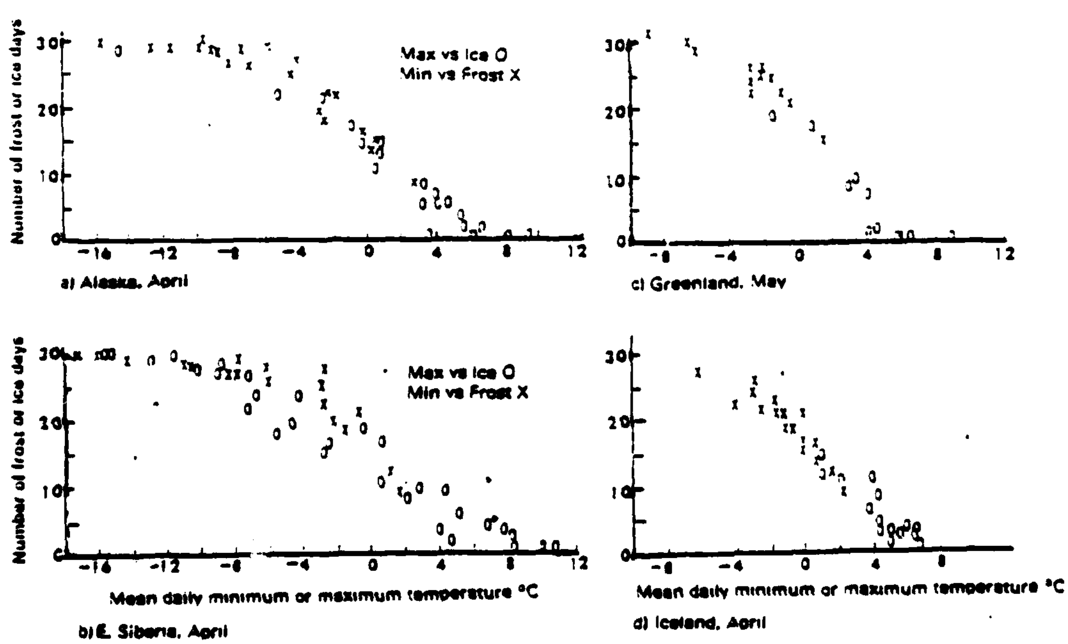

Figure 2 Selected monthly data.

$$F = a_1 + b_1 N \qquad (1a)$$

and

$$I = a_2 + b_2 M \qquad (1b)$$

The parameters a and b depend on the data: They serve as constants for any data set. Table 1 lists values of these constants for monthly and annual data for the above regions. The coefficient of determination, r^2, for the various equations (implied in Table 1) ranged from .50 to .99 with few exceptions: .24 for February, Greenland and .36 for March, E. Siberia. (The value of r^2 indicates the quality of fit between F and N or I and M: 1.0 = excellent fit, 0 = no fit).

Stations were chosen in a given area so as to represent as large a range of temperature as possible. Each pair of equations as (1a) and (1b) is therefore applicable throughout the entire area, with only the parameters M and N changing from station to station.

The parameters (constants) a and b may vary a little with the period of record. If the computations are carried out for M and N in degrees Celsius (as for Table 1), then the value of a equals or approaches half the number of days per given interval of time, that is 160-185 days for the annual data or 12-18 days for the monthly data. An exception is for the annual number of frost days for Greenland, with a = 227. For the annual data, the absolute value of parameter b appears to decrease with continentality, as from 20 for Iceland, a maritime climate, to 6 for E. Siberia, a highly continental climate.

With respect to the monthly data, the value of a tends to be closest to 15 for the months of the transitional seasons, the spring or the fall, when diurnal freeze-thaw cycles are most frequent in this latitude (See Figure 3). Usually the colder the month the higher the value of a, the warmer the month the lower the value of a. Those months for which no constants are given in Table 1 are either too warm (no ice days or frost days) or too cold (all days are frost or ice), therefore no linear relationship. In the computations of the monthly data, the number of frost (ice days) were limited to $1 < F(I) < (n-1)$ where n = total number of days per month.

A comparison between the observed and the estimated annual numbers of frost days or of ice days for test stations is given in Table 2. Values of r^2 for the quality of fit between the observed and estimated frequencies were >.8 for all cases.

FREEZE-THAW DAYS

The number of freeze-thaw days, Z, per given interval of time, a parameter not available in climatic summaries, may be found by a variety of methods, as by direct counting (Williams 1964) or by correlation with ΔT (Fraser 1959, Vischer 1945). In the case of just the crossover of the freezing level, as in this study, Z is simply the difference between the number of frost days and the number of ice days, or

$$Z = F - I \qquad (2)$$

For each area under consideration, the individual equations for annual F and I were first obtained by means of the appropriate constants in Table 1. Then the annual Z may be expressed as follows:

Iceland	$Z = 18M - 20N - 4$	(2a)
Greenland	$Z = 12M - 5N - 60$	(2b)
Alaska	$Z = 14M - 10N - 7$	(2c)
E. Siberia	$Z = 6(M-N) - 16$	(2d)

A comparison between the observed and the estimated annual Z (Table 2) shows somewhat greater discrepancies than in the cases of F and I, the factors on which Z depends. Values of r^2, which indicate the quality of fit between estimated Z and observed Z range from .60 to .76 compared to $> .90$ for F and I (except for Iceland for which r^2 was .84).

Equation (2d) implies that Z may be correlated directly with (M-N) or ΔT for E. Siberia. Fraser (1959) found a similar relationship for Canada, although the cycles he investigated were for a larger temperature span, -2° to 1° C, rather than just across the freezing level.

STATION MODELS OF DIURNAL FREEZE-THAW CYCLES

Station models of percent days per month with diurnal freeze-thaw cycles from January to December are given for selected stations in Greenland, Alaska, Iceland, the U.S.S.R, and West Germany (See Figure 3). For most of the high-latitude stations, especially those close to the Arctic Circle, the peak incidence of diurnal freeze-thaw cycles occurs during the transitional seasons of spring and fall. The stations are arranged so as to show a gradual change in pattern from an extremely cold climate as Barrow, Nord, or Polar Station where diurnal freeze-thaw cycles prevail only in summer to the relatively warm stations of Annette or Vladivostok, which have relatively long summers with no freezing and the peak frequecies of freeze-thaw cycles in the winter. The West German Stations from Zugspitze (2962 m) to Munich (532 m) reflect the effect of altitude on the incidence of diurnal freeze-thaw cycles. The station model for Zugspitze is somewhat similar to that for Barrow (or Polar Station). The plots for the Icelandic stations resemble that of Fichtelberg (or Brocken). At Vladivostok, despite the low latitude, January and December are too cold for freeze-thaw, whereas in Iceland, freeze-thaw occurs all winter.

TABLE 1 Constants a and b for Monthly and Annual Regression Equations

	$F = a_1 + b_1N$		$I = a_2 + b_2M$	
	a_1	b_1	a_2	b_2
		ICELAND		
JAN	19.4	-1.6	15.6	-1.4
FEB	16.7	-1.3	14.2	-2.2
MAR	17.4	-1.4	16.0	-2.1
APR	15.8	-2.1	15.9	-2.3
MAY	15.6	-2.6	9.7	-1.0
JUN	11.5	-1.7		
SEP	12.0	-1.8		
OCT	16.1	-3.0	13.9	-2.1
NOV	14.9	-1.8	14.1	-2.2
DEC	20.1	-1.2	15.9	-2.1
ANN	176	-20.2	180	-17.9
		ALASKA		
JAN	21.1	-0.6	13.8	-1.4
FEB	19.3	-0.7	11.9	-1.3
MAR	20.2	-0.9	12.4	-1.9
APR	14.9	-1.8	13.3	-1.4
MAY	14.4	-3.1		
SEP	15.3	-2.6		
OCT	14.0	-1.8	15.8	-2.1
NOV	15.9	-1.3	12.5	-1.5
DEC	20.7	-0.7	13.0	-1.1
ANN	159	-9.7	166	-13.8
		GREENLAND		
JAN			23.5	-0.4
FEB			17.0	-0.6
MAR			18.4	-0.8
APR			14.6	-1.5
MAY	21.1	-1.4		
JUN	16.3	-2.7		
JUL	7.5	-1.4		
SEP	14.3	-2.5		
OCT			16.2	-2.8
NOV			18.7	-1.3
DEC			21.2	-0.7
ANN	227	-5.3	168	-12.4
		E. SIBERIA		
MAR			16.8	-1.5
APR			14.8	-1.7
MAY	15.1	-1.9	14.6	-1.7
OCT	14.7	-1.9	15.2	-1.5
NOV			16.6	-2.1
ANN	183	-5.6	167	-6.1

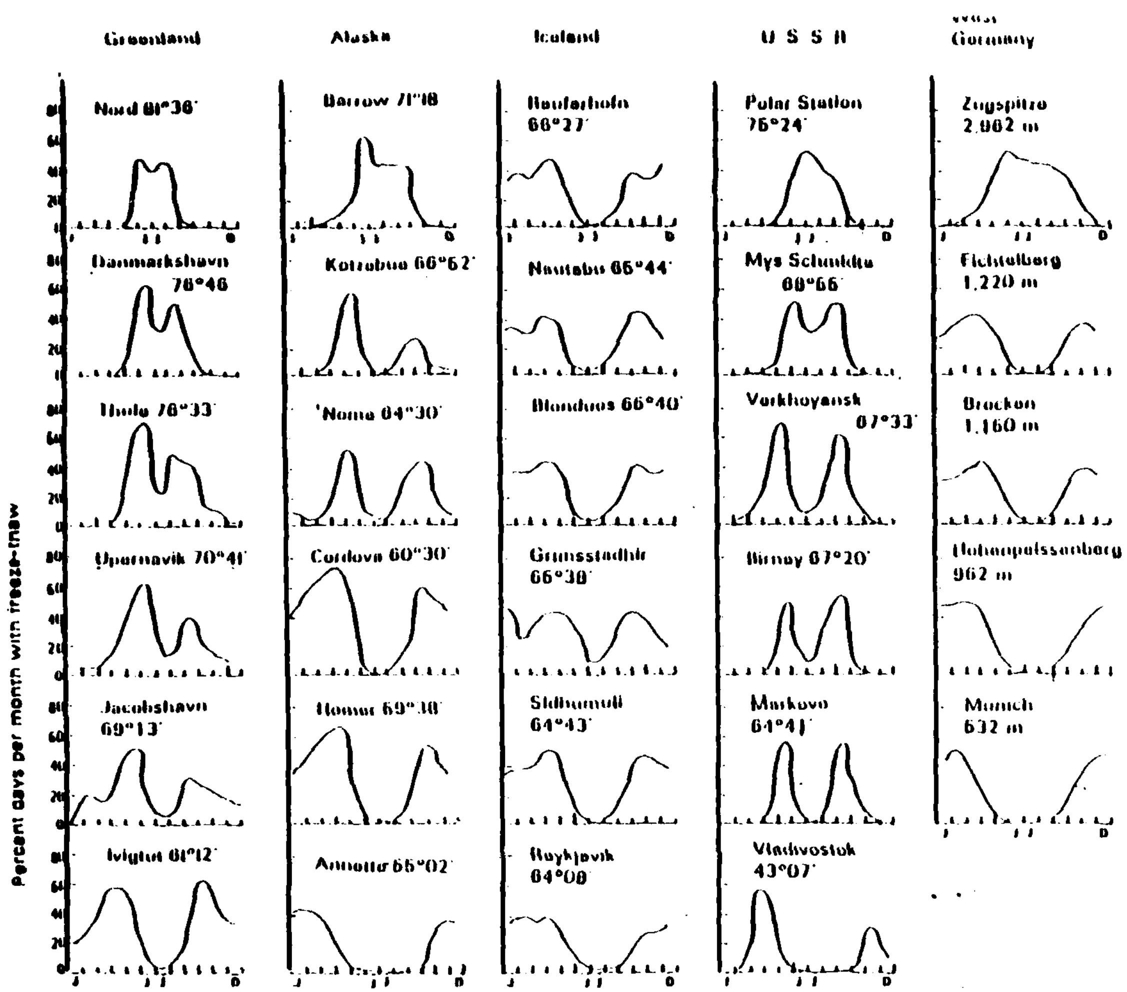

FIGURE 3 Percent days per month with freeze thaw

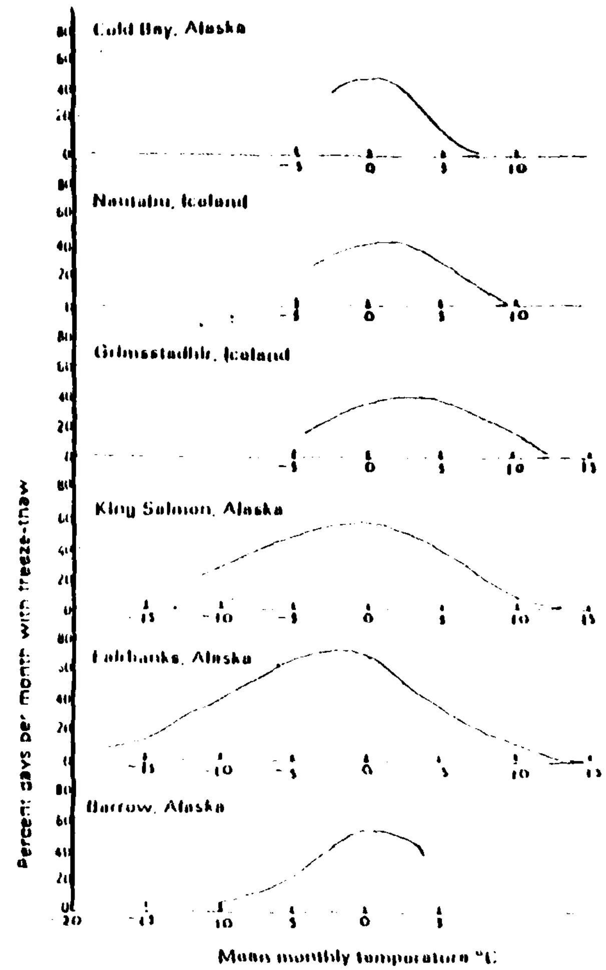

FIGURE 4 Percent days per month with freeze thaw per mean monthly temperature

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TABLE 2 Estimated and Observed Annual Numbers of Frost Days, Ice Days, and Freeze-Thaw Days:

Station	Air Temp ^{o}C	Temp Range $\Delta T^{o}C$	Estimated Number Frost Days	Estimated Number Ice Days	Estimated Number Freeze-thaw Days	Observed Number Frost Days	Observed Number Ice Days	Observed Number Freeze-thaw Days
E. Siberia								
O. Chetyrekhstolbovoy	-13.6	5.0	269	240	29	288	242	46
Dzhardzhan	-12.5	7.2	269	226	43	261	220	41
Zyryanka	-11.4	8.3	266	215	51	253	213	40
Ust Yvdoma	-9.2	11.7	265	189	76	252	181	71
Guga	-3.6	17.2	247	134	113	239	145	94
Nogliki	-2.0	10.5	219	145	74	220	154	66
Sukhanovka	-0.6	10.0	210	138	72	211	149	62
Poronaysk	0.0	8.8	204	138	66	196	136	60
Grossericni	1.2	7.7	194	134	60	188	128	60
Dolinsk	2.3	9.9	194	119	75	192	119	73
Sarychevo	2.5	5.0	179	134	45	189	110	79
Bukhta Preobrazheniya	4.2	10.5	185	105	80	161	79	82
Alaska								
Barter Is.	-12.2	5.9	310	292	18	318	260	52
Summit WSO	-3.9	8.2	239	163	76	251	177	74
Fairbanks	-3.6	11.4	252	137	115	237	157	80
Gambell Is.	-3.4	5.6	221	174	47	256	197	59
Aniak	-2.2	9.5	228	130	98	226	142	84
Naknek	1.5	8.6	187	86	101	204	99	105
Anchorage	1.6	9.2	189	80	109	208	110	98
Cordova	3.1	8.6	171	64	107	184	53	131
Seward	4.0	6.6	152	65	87	160	62	98
Sitka	5.7	7.3	139	38	101	140	21	119
Greenland								
Thule	-11.1	8.4	342	253	89	314	242	72
Upernavik	-7.3	6.7	292	210	82	284	210	74
Jakobshavn	-4.5	6.7	264	173	91	250	183	67
Umanak	-2.8	5.6	242	159	83	253	185	67
Godthaab	-0.9	6.1	225	130	95	254	141	113
Ivgtut	0.8	7.2	214	102	112	221	105	116
Narssag	1.7	6.7	203	94	109	222	96	126
Iceland								
Modhrudalur	0.0	6.6	243	121	122	247	139	108
Raufarhofn	2.5	3.8	164	98	66	177	88	89
Blonduos	3.4	4.5	155	76	79	166	71	95
Egilsstadhir	3.4	6.7	176	56	120	178	72	106
Saudharkrokur	3.6	5.0	154	67	87	143	63	80
Akureyri	3.9	5.6	154	56	98	158	73	85
Haell	4.2	6.1	154	47	107	170	58	112
Loftsalir	5.9	3.9	97	40	57	80	33	47

Another set of station models is shown in Figure 4. This time the abscissa is the mean monthly temperature, however, the ordinate is the same as that of Figure 3, namely the average percent days per month with freeze-thaw. In general, for a given station the daily freeze-thaw cycles per month tend to increase as the mean monthly temperature approaches 0° C. The frequencies per given temperature vary from one station to another. Nevertheless, certain of the models may sometimes serve several stations or groups of stations.

In particular each model shows the temperature limits for its freeze-thaw regime. These limits, as well as the peak amplitudes, are climate dependent.

Station models of this type have also been obtained for numerous other stations in the high and mid-latitudes. A few of these models, as well as an equation which approximates the manual plots in Figure 4, has been given previously (Wexler 1982). See Appendix for the equation. For a highly continental station, as Verkhoyansk (not shown), the freeze-thaw temperature regime extends from about +16 to -16° C with an amplitude of about 68% at about 0° C. Most stations in Iceland have an amplitude of about 40% to 50% with a positive temperature range of about 10° C. Cold Bay, Kodiak, and Annette in Alaska have freeze-thaw regimes similar to stations in Iceland. On

the other hand, interior stations in Alaska have much higher amplitudes, about 70% to 80% as Fairbanks, McGrath, and Gulkana, with temperature ranges from 12° C to -16° C. For a number of stations in Greenland the plots (not given) show much greater irregularities of pattern than for Iceland or Alaska, possibly because of the relatively short periods of records.

SUMMARY

Several mathematical and graphical models were presented for estimating the frequencies of frost days, ice days, and freeze-thaw days per month or year for stations in Alaska, E. Siberia, Iceland, and Greenland. Once linear regression equations are determined for the derivation of frost days and ice days, respectively, per given situation, these equations are then applicable to any site within the area, given only M and N for the site. The frequencies of diurnal freeze-thaw cycles then may be readily obtained from the difference between the frequencies of the frost days and the ice days. The results show that usually diurnal freeze-thaw cyles may not be derived from mean temperatures alone: Essential parameters are the mean daily minimum and mean daily maximum temperatures. The latter yield definitive information concerning frost days, ice days, and freeze-thaw days.

Two types of station models were provided, the first the conventional annual cycle of monthly freeze-thaw and the second, the same data plotted per mean monthly temperature. Although the models tend to be distinctive, each depending on latitude (solar elevation), altitude, continentality, and local conditions nevertheless certain of the models may be used to represent groups of stations.

Despite the differences among the areas, an interesting feature of this study is the apparent universicality of the linear. The annual number of frost (ice) days ranged roughly from about 230 to 100 within the minimum (maximum) temperature range of -5° to $+5^{\circ}$ C. All the days of the month were usually below freezing if the mean maximum temperature was $< -6^{\circ}$ C and above freezing if the mean minimum temperature was $> 6^{\circ}$ C. Usually the number of frost (ice) days associated with 0° C was equal to about half the number of days per given interval of time.

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APPENDIX

An equation which roughly approximates the manual plots in Figure 4 is given by:

$$y = a \sin Q \tag{3}$$

where y = % days per month with freeze-thaw

a = amplitude of curve (peak % monthly freeze-thaw)

Q = $1.57\,(T + b)/b$

b = $T_{ym_a} - T_{ym_0}$

T_{ym_a} = temperature at peak % (usually 0°C).

T_{ym_0} = temperature at which freeze-thaw is nil = cut-off temperature.

T = mean monthly temperature ($^{\circ}$C)

NOTE: If the peak % frequency is not at 0° C, let d = departure from 0° C and substitute T-d for T.

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